RF-to-Millimeter Wave AC Conductivity of Carbon Nanotubes

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Motivation—Carbon nanotubes (CNTs) are predicted to have novel electrodynamic properties that could be exploited to push nanotechnology into the rf-thru-millimeter wave frequency domain. For example, pure CNTs are thought to support ballistic charge transport that can be used to construct power-efficient, frequency-agile oscillators and detectors. Chemically functionalized with molecule-specific receptors, CNTs can serve in an entirely new capacity: *chemically* tunable AC components for ultra-sensitive chem/bio sensors. Development of CNTs for high frequency will require far more advanced empirical knowledge of basic electrodynamic properties than exists. This is particularly true in view of the suspected ballistic nature of charge transport, which if true means that the conventional Drude model of high frequency conductivity will not apply. The goal of our research is to perform experiments that will elucidate clearly and quantitatively the electrodynamic properties of CNTs.

Accomplishment—We designed and fabricated a broadband, flexible experimental platform to measure the real and imaginary conductivity of CNTs from 0.01 to 50 GHz in frequency and from 300 K down to 4 K in temperature. The experimental platform is based on a co-planar waveguide (CPW) onto which CNTs are directly assembled across the dielectric gaps, see Fig. 1. The difficult constraint was that the CPW dimensions had to be large enough so that the waveguide impedance remained approximately 50 Ω to match the high-frequency measurement instrumentation impedance, and small enough to support CNT directed assembly by AC dielectrophoresis. The AC dielectrophoresis method offers reasonably well-controlled numbers of CNTs to be assembled on the CPWs so that the CNT axis is polarized along the electric field of the propagating electromagnetic radiation in the waveguide mode.

We measured the CPW's complex reflection and transmission coefficients before and after CNT assembly using a vector network analyzer on a broadband probe station. Initial results are shown in Fig. 2. Clearly observable are changes in reflection and decreased transmission (i.e. increased dissipation) due to the CNTs. Interestingly, characterization of these first samples indicate that only a very small number of individual CNTs assembled at a few random positions along the 5 mm waveguide. The reflection oscillations shown in Fig. 2 are believed to arise from the interference of reflections by a few CNTs along the waveguide. While we cannot yet determine the exact number and positions of the CNT assembly, these data show that our measurement methods are sensitive to only a small number of CNTs.

Significance—The data shown in Fig. 2 represent the first broadband measurement of the intrinsic rf-to-millimeter wave AC conductivity properties of CNTs. Once we have refined the experimental procedure so that the assembled CNTs can be counted and localized, such data will deliver clear and quantitative information about the important physical electrodynamic properties of these widely used nanomaterials. This knowledge and the techniques we develop will open the door to exploiting CNT nanotechnology in high-frequency devices.

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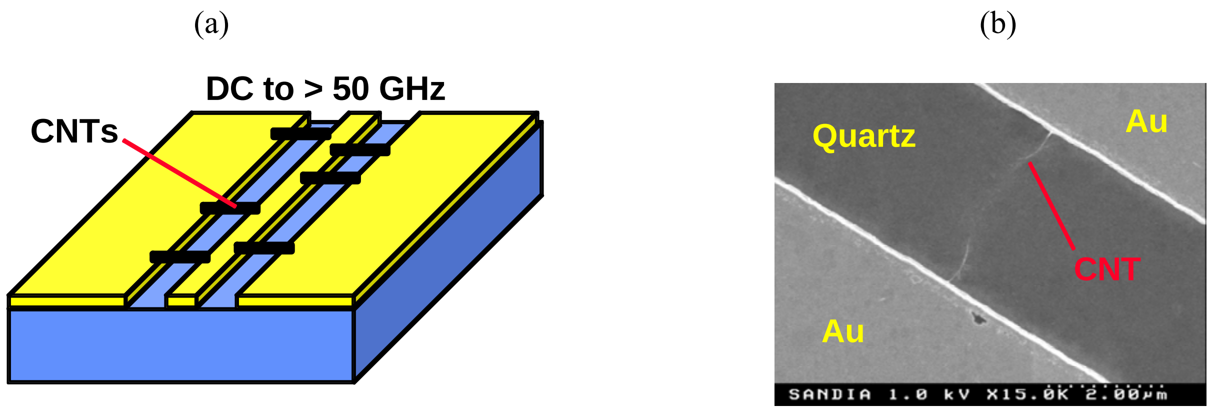

Figure 1. (a) Sketch of a broadband co-planar waveguide geometry. The yellow indicates gold electrodes, and the blue represents the dielectric substrate. A few carbon nanotubes (CNTs) are depicted assembled across the gaps. (b) Plan view scanning electron micrograph of a single CNT assembled across a 3 μm wide quartz gap in a co-planar waveguide. The CNT is continuous but sags slightly out of the focus plane in the center of the gap.

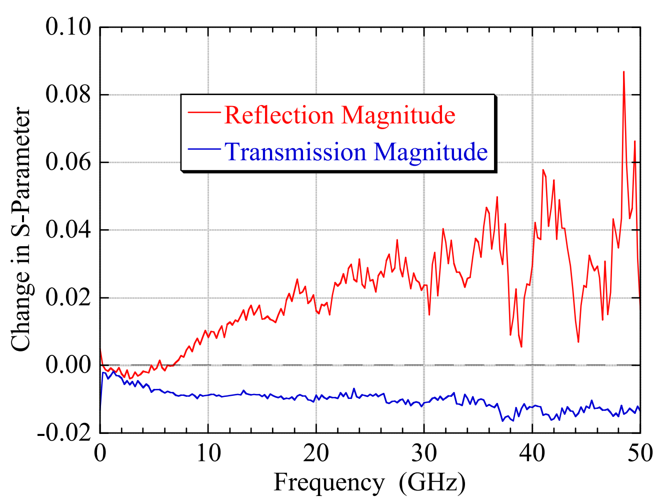

Figure 2. Change in reflection and transmission magnitudes as a function of frequency for the same co-planar waveguide before and after CNT assembly by AC dielectrophoresis. This waveguide was assembled in the same manner as the one depicted in Fig. 1(b). A reference waveguide on which no CNTs were assembled showed no measurable change in repeated measurements.